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GROUND TESTING KINETIC ENERGY PROJECTILES FOR THE LIGHTWEIGHT EXO-ATMOSPHERIC PROJECTILE (LEAP) PROGRAM

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Abstract

Research into the use of kinetic energy weapons (KEWs) for the Strategic Defense Initiative Organization's (SDIO) Lightweight Exo-Atmospheric Projectile (LEAP) program has led to various designs for advanced, rocket controlled kinetic kill vehicles (KKVs). With the development of these high performance vehicles, the need arose for an extensive ground test program to reduce the risks associated with final qualification space flights. With this low risk, observable ground test philosophy in mind, the National Hover Test Facility (NHTF) was selected as the location of the first full up test operations of the LEAP designs. The primary objective of testing space interceptors in a ground based, controlled hover flight environment is to verify complete and full up operations and performance of all subsystems functioning in unison as an integrated interceptor prior to commiting to a space test.

The NHTF's test schedule for 1991 revealed a full calendar with a barrage of tests planned in support of the various phases of the LEAP program. The primary LEAP support plan consisted of the first full up checkouts of two entirely different flight vehicles as the U.S. Army and U.S. Air Force developed their own projectiles with specific missions in mind. This paper will address the NHTF's support to the SDIO's LEAP program by detailing the events involved in the ground testing phase of the program and highlighting results of this extensive testing.

Abbreviations

LEAP	Lightweight Exo-Atmospheric Projectile
KEW	Kinetic Energy Weapon
SDIO	Strategic Defense Initiative Organization
KKV	Kinetic Kill Vehicle
NHTF	National Hover Test Facility
KHIT	Kinetic Kill Vehicle Hovered Interceptor Test
IMU	Inertial Measurement Unit
EHV	Experimental Hover Vehicle
IR	Infra-red
ONTARGET	On-board Navigation, Transition and Realtime Guidance Experiment Test
AHIT	Advanced Hovered Interceptor Test
CG/MOI	Center of Gravity/Moment of Inertia
TM	Telemetry
DAS	Data Acquisition System
CST	Combined System Test
NTO	Nitrogen Tetroxide
RF	Radio Frequency
ADS	Advanced Decommutation System
GTP	Ground Test Projectile
ACS	Attitude Control System
HAPC	High Accuracy Propellant Cart
EO	Electro-Optical
IFOG	Interferometric Fiber Optic Gyro

NHTF History

The NHTF, located at the Phillips Laboratory's operating location Edwards AFB, CA, was developed under the kinetic kill vehicle hovered interceptor test (KHIT) program to provide ground test capabilities for researching KKV technologies. Comprised of an approximately 115 foot by 50 foot hangar with a 70 foot (l) by 30 foot (w) by 20 foot (h) flight volume entirely enclosed by a reinforced capture net, the NHTF provides the unique capability of testing fully integrated interceptors in a controlled, observable and repeatable environment. Adjacent to the flight hangar is the control room where the test personnel perform the countdown sequences during testing which include: telemetry checks with the vehicle, seeker targeting checks, vehicle inertial measurement unit (IMU) biasing, propulsion system remote pressurization as well as overall projectile status monitoring. A direct view of the test article is available through the observation booth joining the hangar and control room and provides the ideal location for the range safety officer during testing. Figure 1 shows a layout of the area the NHTF encompasses with support buildings and target locations.

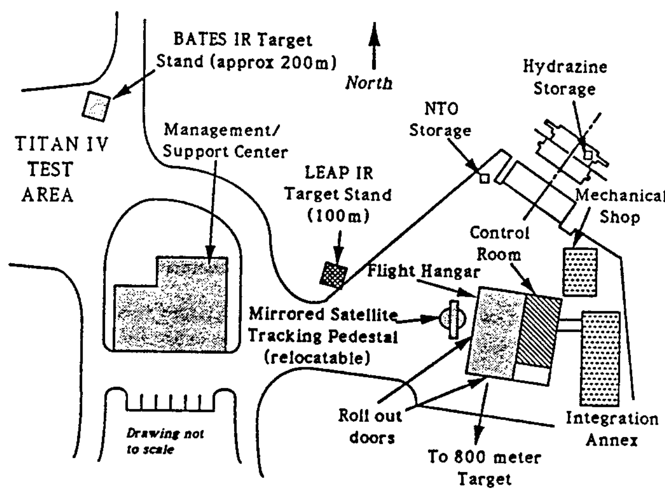


FIG 1
NATIONAL HOVER TEST FACILITY'S LAYOUT

The first tests at the NHTF involved the KHIT experimental hover vehicle (EHV) and culminated in April 1989 with the first full up hover test of a KKV prototype. During the 24 second flight, the 200 pound EHV, using its bipropellant rocket engines, maneuvered through a preprogrammed hover flight trajectory and safely landed in the capture net. With this milestone in the development of KKV technologies, the path was paved for advances in vehicle systems and performance including: avionics, inertial guidance and control, seekers, communications and propulsion.

The follow-on program to KHIT introduced an infrared (IR) seeker on-board the EHV and integrated it into the guidance control loop. The main objective of this On-board Navigation, Transition and Realtime Guidance Experiment Test (ONTARGET) was to hover the now 220 pound EHV with control commands originating from the output of the seeker's image processor. Two hover flight tests were performed in August and September of 1989 in which the EHV lifted off its cradle supports, locked on and tracked a solid rocket motor firing 200 meters away and transitioned to a simulated missile hardbody just below the burning motor. These tests successfully demonstrated the capability of performing a KKV full up flight while tracking a simulated hostile target's plume and accomplishing the critical plume-to-hardbody handover algorithms required to intercept the desired target.

The next program to utilize the facility was designated the Advanced Hovered Interceptor Test (AHIT). During this program breakthroughs in propulsion systems and avionics miniaturization were made creating a lighter weight (40 pound) projectile with greater performance capabilities than its predecessor. The AHIT vehicle completed its hover test in July

NHTF Capabilities

The general support capabilities of the NHTF include a variety of test equipment and personnel necessary to support ground testing of KKVs. These capabilities include: projectile center of gravity/moment of inertia (CG/MOI) determinations, liquid propellant loading/detanking/decontamination operations, propellant system high pressure gas operations, telemetry (TM) and data acquisition systems (DAS), visible and IR targeting, photographic and video coverage, range safety system monitoring and a complete projectile launch system. The hardware has been qualified repeatedly with the completion of extensive combined system tests (CSTs), which are essentially countdown simulations, during which a minimum of two perfect CSTs are required prior to commiting to a hover flight test for any given program. The NHTF team provides the crucial experience needed to develop the program specific hardware configurations and procedures that allow complete projectile checkouts without the risk of damage to hardware.

Some general NHTF assets follow with specific test program requirements resulting in modifications/upgrades to the baseline hardware.

CG/MOI - In order to maintain vehicle control during hover testing, it is essential to ascertain the location of the center of gravity (CG) and moments of inertia (MOI) of the KKV prior to liftoff. To determine this data, the NHTF relies on a Space Electronics KSR-330 mass properties instrument. The KSR-330 can accurately measure the CG in three axes to within 0.0004 inch and MOI to within +/- 0.25 percent while carefully cycling the KKV through a series of computer controlled oscillations. Because the CG has a tendency to travel during propellant expulsion as the KKV flies, the CG is manipulated to an optimum position prior to launch. This is accomplished by placing calibrated weights on the projectile in precisely calculated locations, thus eliminating the likelihood of a severe CG shift during flight resulting in an unstable vehicle. The moments of inertia of the KKV in all three axes are determined using the KSR 330's gas bearing, internal brake system and torsional pendulum of known stiffness. With the valuable CG and MOI data known along with other vehicle specific parameters, the NHTF simulation team calculates accurate hover trajectory data to begin the process of range safety system analysis.

PROPELLANT OPERATIONS - The NHTF has storage areas for nitrogen tetroxide (NTO) and hydrazine based fuels as well as the equipment and personnel necessary to load, decontaminate and neutralize them on-site. Propellant loading operations are performed by NHTF personnel who are trained and qualified to work on the red crew, which handles all hazardous propellant servicing operations. Propellant servicing is done using a complete set (oxidizer and fuel) of self-contained loading and decontamination carts. The NHTF currently has two types of propellant transfer carts and a third type will soon be completed.

PROJECTILE PRESSURIZATION - High pressure helium and nitrogen servicing is available for vehicle propulsion system pressurization. The NHTF has three 20,000 psi man rated pressure carts and support hardware capable of remotely pressurizing a vehicle's propulsion system to a desired level for test. These carts were acquired through the air launched antisatellite program conducted at Edwards AFB and have been used extensively both at the NHTF and other range facilities.

TELEMETRY - In the absence of hardwire connections to free flying hover vehicles, radio frequency (RF) TM is the standard for communicating with the hovering KKV during testing. The only exception to this was the use of a fiber optic link during the Army LEAP program testing that will be discussed later. The NHTF has a full complement of L-band and S-band telemetry receivers for downlink data collection as well as both S-band and UHF transmitters for uplink communication and range safety functions respectively. A combination of directional antennas and anechoic foam provides a clean RF TM environment within the metal building for both uplink and downlink transmissions. Real time data processing and recording is accomplished using the NHTF's advanced decommutation system (ADS-100) and magnetic tape drive systems.

KKV TARGET SOURCES - The NHTF has developed a wide range of target sources in both the visible and IR spectrums which provide the realistic KKV targeting capabilities required for active tracking during seeker checkouts and terminal tracking during full flight missions. These targets range in complexity from calibrated ceramic heating elements to moving point sources of light to remotely fired solid rocket motors. Varied target locations also exist with current targets available at 10, 100, 200 and 800 meters from the launch cradle. Additional target sources and distances are currently being evaluated as candidates for upcoming programs. For more details regarding the NHTF's targeting capabilities see Reference 1.

PHOTO/VIDEO - The NHTF is equipped with a full complement of photographic and video equipment that provides coverage of the entire test area for documentary and post test analysis purposes. High speed still and motion picture cameras are available that allow up to 2000 frames per second coverage on the faster moving tests. Twelve video cameras provide real time coverage with up to six views displayed to the test crew in the control room and to visitors in the conference room in the management/support building. Relocatable video cameras are also used during the fueling operations to remotely monitor progress along with the projectile and fuel cart conditions. In all, a total of 30 cameras provide crucial documentation of all test operations.

KKV CRADLE LAUNCH SYSTEM - The test vehicle launch system used during hover flights consists of two hydraulically controlled scissor jack platforms mounted together and remotely operated from the control room. Mounted atop the platform is a customized cradle that is designed specifically for a given vehicle and securely holds the test article in position. A leveling system is incorporated into the launch system that remotely levels the vehicle in pitch and roll while allowing manual control over yaw. The entire system is capable of extending upwards in excess of 10 feet above the hangar floor and retracts automatically when triggered by a microswitch that senses the KKV liftoff. Figure 2 shows the launch system layout with a representative KKV in liftoff position.

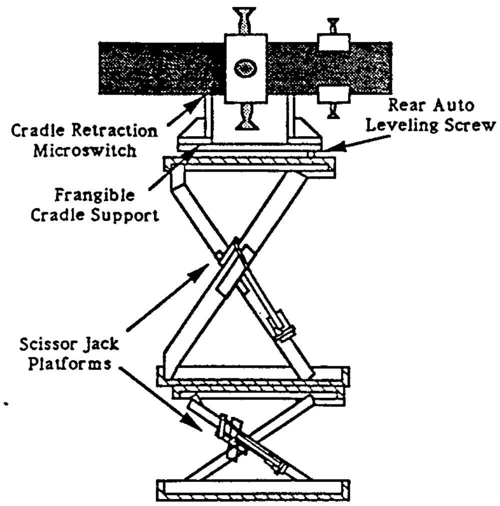


FIGURE 2
KKV LAUNCH CRADLE

LEAP PROGRAM TESTING

Although all of the above NHTF capabilities were made available to the LEAP program, some specific contractor modifications were required. A unique asset of the NHTF is its flexibility to allow real time modifications to facility and test support equipment in order to support specific missions. The close proximity of the Army and Air Force LEAP programs' arrival at the NHTF posed the problem of two contractor teams being able to build up and integrate projectiles simultaneously within a limited space while also maintaining control over competition sensitive material. Facility modifications were required which included the addition of an integration and checkout building complete with a large clean room and an additional contractor ground support equipment area within the main control room. These upgrades, as well as mutual respect among the contractor teams, sufficiently squelched any concerns regarding proprietary information.

Test support equipment modifications for the LEAP program included the design and fabrication of advanced propellant servicing carts, the design, construction and subsequent upgrade of an infrared target stand as well as upgrades to existing facility equipment. These modifications will be outlined as they relate to the two separate programs.

U.S. Army LEAP

The U.S. Army's program was the first to enter full up testing at the NHTF with the arrival of their LEAP vehicle and support test equipment in mid-March 1991 for integration and checkout. Designated the LEAP-2 Ground Test Projectile (GTP), this system was designed and fabricated by Hughes Aircraft Company, Missile Systems Group and has the distinction of being the lightest weight, fully autonomous kinetic energy projectile developed to date. The GTP (shown in Figure 3) consists of advanced, high performance components which include: a high resolution mid-wave IR seeker with accompanying target acquisition and tracking computer, miniaturized avionics with high density electronics, a fiber optic telemetry transceiver and an inertial measurement unit. All of these components are tightly packaged around a miniaturized liquid bipropellant propulsion system, developed by the Marquardt Company of Van Nuys, CA, that keeps the flight weight of the LEAP-2 GTP under 15 pounds. Four hypergolic divert engines, one of which is not utilized for tests at the NHTF, provide the main thrust for the GTP while a hydrazine warm gas generator provides the propulsive power for the 8 attituded control system (ACS) engines.

Prior to the LEAP-2 GTP hardware delivery, the NHTF personnel began facility modifications in support of the two scheduled test firings; one full up vehicle strapdown static test and one hover flight test. Due to the miniaturized state of the LEAP-2 GTP, highly accurate (within two grams) propellant transfer operations are required to ensure that precise quantities of the liquid propellants (hydrazine and NTO) are loaded prior to testing. To meet this requirement, new propellant loading carts had to be developed to support the mission. With support from the Jet Propulsion Laboratory, two high accuracy propellant carts (HAPCs) were designed and built for the fuel and oxidizer to complete the hazardous operations. Based on a differential pressure transducer measurement across a column of propellant being transferred, the HAPCs are mobile systems capable of loading hydrazine or NTO into a system with an accuracy better than 0.75 percent. Since the LEAP-2 GTP's two cylindrical fuel tanks and two cylindrical oxidizer tanks are each filled with approximately 200 grams of fuel and oxidizer prior to flight, the HAPCs ensured the accuracy requirement was met.

Along with the new propellants carts, a new IR target stand was required to provide tracking capabilities at 100 meters from the flight test area. Rising to the challenge, a 30 foot tall target stand was built consisting of a 10 foot square uniform target background with a centered 4 inch square opening. Located behind a remotely activated viewing plate at the square opening is a series of calibrated heating elements with filters that provides the primary IR signature target. Included in the target design are additional alignment targets that ensured proper positioning of the LEAP-2 GTP on its launch cradle prior to liftoff. These alignment sources are two 100 watt incandescent light bulbs aligned vertically above and below the primary target and positioned behind 2 inch square covers on the target background. The entire background and target system is capable of vertical travel via an electric hoist, thus allowing for varying target heights during seeker checkouts and actual strapdown and hover testing. Prior to full up vehicle testing, the alignment lights are turned on and the seeker system activated. As the targets are viewed by the seeker, data is examined real time to determine roll, pitch and yaw position of the GTP in its cradle. If the position is not precise, the leveling system is activated and the cradle adjusts to position the GTP in the desired orientation for test.

Another facility feature required for testing the LEAP-2 GTP was the addition of a post test cooling system capable of reducing the GTP's propulsion system temperature rapidly to avoid the risk of component damage due to heat soak-back at test completion. This cooling requirement ensured flight hardware reusability with minimal projectile refurbishment between the two planned tests. Three large fans were manufactured to provide the airflow required to bring the vehicle's exterior temperature down quickly. Two of the fans were strategically positioned on maneuverable pedestals in the flight hangar to allow cooling coverage to all areas within the recovery net.

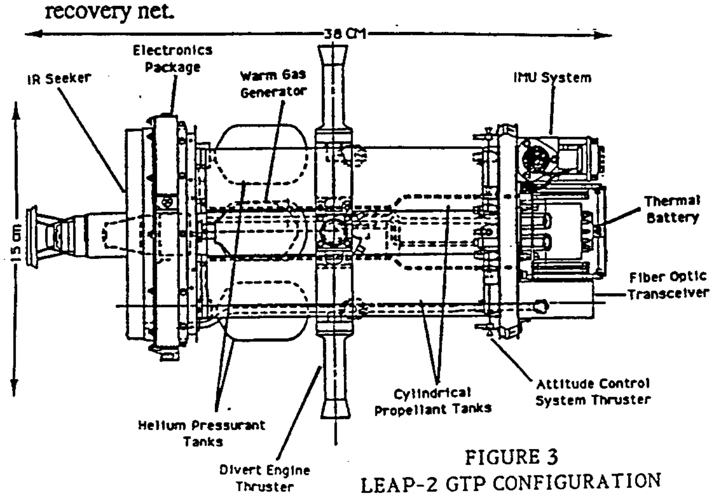


FIGURE 3
LEAP-2 GTP CONFIGURATION

With the GTP's arrival on March 19, 1991, the final phase of facility integration began leading to a fully integrated LEAP-2 GTP strapdown test. With the final pretest operations reaching completion in the end of March, the schedule was forced to slip when the flight hangar was damaged following the explosion of the Titan IV solid rocket motor during a static firing at an adjacent test stand. After completing repairs to NHTF assets in record time, test operations resumed and the GTP was mounted with instrumentation to monitor voltages, accelerations, temperatures and pressures. A propellant loading practice run was completed using a simulated GTP propellant tank system with the HAPCs to ensure all elements of the hazardous process ran smoothly during the actual operation. The CSTs then followed during which the 8 hour countdown leading up to the test was practiced thoroughly to ensure the procedures, support equipment, test crew and GTP were ready for test. A total of 5 CSTs were accomplished and, on April 21, the GTP propellant loading process began.

Following the propellant loading, the GTP was rigidly attached to the lowered scissor jack launch platform and the final instrumentation checkouts were performed. On the morning of April 23, 1991, the countdown commenced and culminated with the first full up firing of the LEAP-2 system. During the full duration 10 second test, the GTP performed a preprogrammed engine firing sequence representing both a hover test duty cycle and a space test mission. The 3 active divert engines fired approximately 100 times and the 8 ACS engines fired over 1400 times while the seeker tracking system maintained lock on the distant target. All the projectile internal data accumulated (including projectile health and status as well as seeker imagery data) was downlinked to the ground support equipment via a fiber optic link. Because of the weight constraints associated with conventional RF TM systems, the fiber optic communication system was utilized with the GTP. This method of data capture proved ideal in gathering and recording the large quantities of data being transmitted at the high rates.

With the completion of this milestone test, post test inspection of the GTP hardware and review of the data gathered, the test was stamped a complete success. The stage was now set for the removal of the restraint system required for the strapdown test and facility modifications to accommodate a free flight. Due to the complexity of the cradle launch system provided by Hughes, a large access hole in the bottom of the recovery net was required to allow the GTP and launch cradle to protrude into the flight volume. This hole presented the problem of ensuring that the free flying GTP did not fall through the recovery net and impale itself on the cradle or hit the concrete floor. To meet this challenge, an access hole closure system was developed to quickly seal the hole at GTP liftoff. The system, triggered by the automatic lowering of the launch cradle, activates a weight and pulley combination that securely seals the access hole within two seconds of initiation.

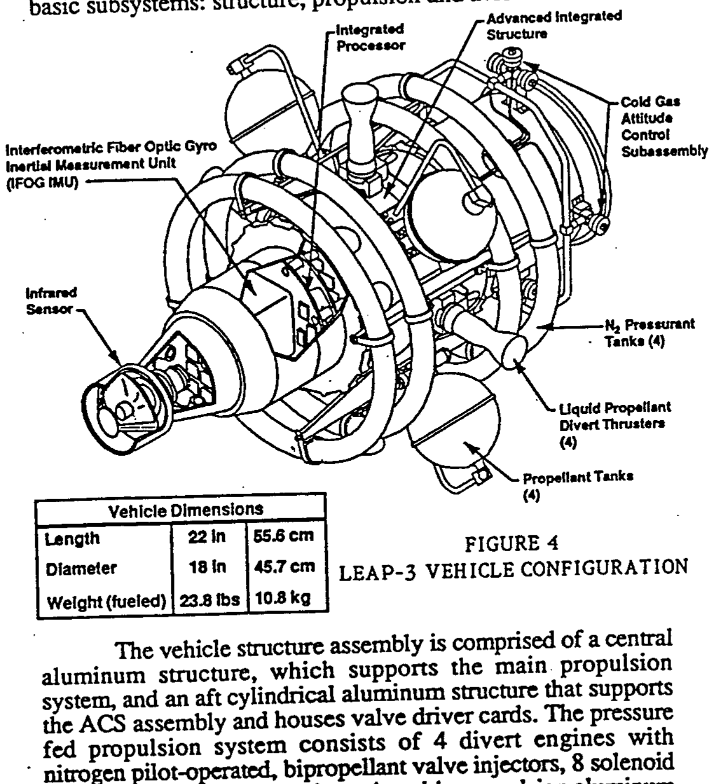
As the NHTF began reconfiguring for the hover test and modifying procedures accordingly, the GTP returned to Hughes for a detailed examination, refurbishment and hover test modification process. With all systems performing well in the lab and following a detailed acceptance test program, the GTP returned to the NHTF the first week of June with all systems go for flight. After being reintegrated into the facility and completing three successful CSTs (the fewest ever accomplished with all goals met for a test), the facility and test personnel were ready for final preparations. The propellant loading process commenced on June 15 followed by the CG/MOI measurement and subsequent CG balancing.

On the evening of June 18 the final countdown began as the test conductor initiated the flight day Master Countdown checks. All systems performed flawlessly as the GTP was elevated to her launch position 10 feet above the hangar floor and was leveled in the cradle and aligned with the target. As the leveling was completed, the high pressure gas cart was brought on-line to remotely deliver the 10,000 psi of helium to the three on-board propulsion system pressurant tanks.

The terminal countdown followed the pressurant fill as the computer driven autosequence was activated. At T-25 seconds, the GTP was commanded on and began a series of diagnostic checks, each one having an out of specification abort criterion. Following the successful progression of the start up sequence, the GTP's internal thermal battery was activated and all power was transferred to the on-board source as the umbilical remotely retracted. At T=0 seconds, the on-board terminal intercept guidance program, which had been slightly modified to achieve stable hover, was engaged and the GTP proceeded to lift off its cradle support with the first engine command. The GTP quickly rose to an altitude of 20 feet above the floor while continuously tracking its target. At T+5 seconds, the terminal guidance software hover flight limiters were released and the GTP propulsion system commanded maneuvers to simulate an actual intercept. With the "successful intercept" completed at T+6.9 seconds, the GTP performed a flight termination command and safely landed in the capture net 9 feet back from the launch point as planned. The full duration flight was a complete success as the GTP met or exceeded all mission criteria while only using approximately thirty percent of its fuel load.

Air Force LEAP

During the final preparations for the Army LEAP-2 hover test, the team of Boeing Aerospace and Electronics and Rockwell International, Rocketdyne Division were packaging the Air Force's LEAP-3 projectile for delivery to the NHTF. This projectile arrived unassembled and was integrated at the facility by interfacing Boeing's avionics, IR seeker and communication package with Rocketdyne's propulsion system. The LEAP-3 projectile (shown in Figure 4) is divided into three basic subsystems: structure, propulsion and avionics.



Vehicle Dimensions		
Length	22 in	55.6 cm
Diameter	18 in	45.7 cm
Weight (fueled)	23.8 lbs	10.8 kg

FIGURE 4
LEAP-3 VEHICLE CONFIGURATION

The vehicle structure assembly is comprised of a central aluminum structure, which supports the main propulsion system, and an aft cylindrical aluminum structure that supports the ACS assembly and houses valve driver cards. The pressure fed propulsion system consists of 4 divert engines with nitrogen pilot-operated, bipropellant valve injectors, 8 solenoid operated cold gas ACS engines, 4 positive expulsion aluminum propellant tanks and 4 titanium toroidal nitrogen pressurant tanks. The Boeing supplied avionics package consists of an electro-optical (EO) sensor, an interferometric fiber optic gyro (IFOG) IMU, a Boeing designed integrated processor computer and a RF TM system. Once in final configuration the approximately 20 pound vehicle underwent extensive checkouts leading to a full up hover test. Since the LEAP-3 propulsion system is essentially identical to that flown successfully during the AHIT program, a static strapdown test was not required.

Prior to the Air Force LEAP hover test, several pretest preparations were required in order to ensure a successful test. The use of an on-board L-band transmitter for data transfer and an on-board UHF command receiver for range safety made it necessary to verify the communication links between the projectile and the ground station. Drop outs in the L-band downlink would result in loss of crucial data and the loss of UHF uplink would result in a premature flight shutdown. In order to verify the integrity of these critical links, telemetry testing was done within the confines of the hangar with the actual flight hardware. The difficulty in suspending the actual projectile in the flight envelope and supplying the required avionics and seeker cooling ruled out the use of the full flight projectile for the checkout. In order to compensate, the flight transmitter, command receiver and antennas were placed on a LEAP-3 engineering model and suspended from a hoist located on the hangar's ceiling. The model was then maneuvered through the planned hover flight envelope and signal strength data was recorded from the antennas. This data was used to perform a link analysis to determine the optimum transmitter power required to allow continuous communication with the projectile during flight.

Additional checkouts were performed on the LEAP-3 DAS during which the projectile was powered up from ground power and data was transmitted to the receiving station. In this flight set up, the projectile's L-band downlink TM stream was received using the facility's parabolic dish antenna and ground receiver. The data was then sent to the Boeing DAS for processing as well as to FM tape for recording. The processed data stream was then relayed to the NHTF's ADS-100 where key projectile health and status information was displayed real time to the test engineers.

Another support requirement for the LEAP-3 test was modifications to the IR target stand built for the LEAP-2 test. Due to the narrow field-of-view seeker on-board the LEAP-3 projectile, a second IR target complete with a uniform background had to be attached to the existing stand. The LEAP-3 test profile required viewing the IR target just prior to liftoff and reacquiring it again at flight altitude. Since this was not possible with the existing target, construction of an additional 10 foot square background and IR source was required. This second target was secured to the stand at the projectile launch height for seeker checkouts prior to liftoff while the original target was fixed at the predicted hover height. Seeker calibration was accomplished using the lower target and maintained by adjusting the upper target temperature remotely from within the control room.

On August 22, 1991 following the propellant loading operations, the LEAP-3 projectile was ready for test. Following the extensive countdown sequence, the projectile successfully lifted off its cradle and maneuvered through the flight volume while viewing its target. Once at its hover altitude of 20 feet, the projectile performed a series of lateral 5 g maneuvers to simulate accelerations required to intercept targets in an actual space engagement. The successful 17 second flight ended as the projectile vented its propulsion pressurization and fell into the recovery net. With the completion of this test of the highest performance projectile developed to date, the LEAP 1991 ground test program was complete and the analysis phase was ready to commence on the wealth of data accumulated.

Conclusions

The NHTF has once again successfully completed a major test program within a time frame not usually achievable in the realms of flight test operations. In this case three entirely different tests, each having its own individual mission specific support requirements, occurred within four months of each other. As the wealth of data from these tests begins to be analyzed and studied, further engineering advancements will result that will carry over to future programs.

Meanwhile, the LEAP program is continuing on to its next phase of testing with suborbital space flights out of White Sands Missile Range, New Mexico. The NHTF LEAP support will also continue as the experience and lessons learned are carried over to this second phase as hardware and test personnel used during the hover flight phase follow the program to the field. This means of maintaining commonality throughout the life of a flight test series increases the probability of success as a program matures as has been proven during the initial phases of the SDIO LEAP technology program.

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